

## EXTENSION OF $M_s$ (VMAX) TO GLOBAL PATHS

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### **ABSTRACT**

Recent work with a prototype application for variable-period Rayleigh-wave magnitudes (Russell, 2006) has reported use of the  $M_s$ (VMAX) technique for periods between 8 and 25 seconds (Bonner et al., 2006a, 2006b, 2007). More recently, the technique has been extended to 40 seconds (Bonner, 2007). In all previous studies, the data were limited to continental paths and thoroughly reviewed.

This study has attempted to evaluate an operational scenario whereby all surface-wave paths are considered. Two groups of data have been utilized, twenty-seven (27) shallow events from the Asian continent and a larger (143 events) global event group with a broader depth range. All events have been reviewed by an analyst for validity. To obtain a better understanding of period and path effects, the data have been subdivided into three period ranges (8–17 seconds, 17–25 seconds, and 25–40 seconds) and separated by predicted group slowness into oceanic paths ( $slow < 32.25$  sec/deg), continental paths ( $slow > 38.0$  sec/deg), and mixed oceanic-continental paths ( $32.25 \text{ sec/deg} \leq slow \leq 38.0 \text{ sec/deg}$ ).

Past studies have demonstrated the  $M_s$ (VMAX) technique works well for continental paths between 8 and 25 seconds (Bonner et al., 2006b, 2007). This study shows stable results for all paths (oceanic, mixed, and continental) between 8 and 25 seconds. Since the data have been shown to be path independent, the  $M_s$ (VMAX) technique may provide an automated replacement for  $M_s$ , allowing the inclusion of regional stations with Airy phases and reducing the analyst burden.

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## OBJECTIVES

Our objective is to extend and evaluate the  $M_s(\text{VMAX})$  magnitude calculation on a global scale, utilizing all available station paths, rather than being limited to continental paths. Extending the technique to all surface-wave paths is an important step towards automating the process in an operational monitoring environment, where manual analysis and calculation are not feasible for all events.

## RESEARCH ACCOMPLISHED

**Background.** Russell (2006) developed a magnitude equation, called  $M_s(\text{VMAX})$ , which was originally intended for surface wave paths through typical continental crust, however, it was unclear how well the original equation would extend beyond continental paths to other paths (oceanic or mixed continental-oceanic). The equation is

$$M_{s(b)} = \log(a_b) + \frac{1}{2} \log(\sin(\Delta)) + 0.0031 \left( \frac{20}{T} \right)^{1.8} \Delta - 0.66 \log(f_c) - 0.43$$

where  $T$  is the period,  $a_b$  is the amplitude of the Butterworth-filtered surface waves,  $\Delta$  is the distance in degrees, and  $f_c \leq \frac{0.6}{T\sqrt{\Delta}}$  is the corner filter frequency of a third-order Butterworth band-pass filter with center period  $T$  and

bandwidth  $2f_c$ . The  $M_s(\text{VMAX})$  method allows measurement of surface-wave magnitudes at both regional and teleseismic distances, while conventional  $M_s$  measures magnitudes at teleseismic distances with periods between 17–23 seconds.

Methodologies using this approach have been presented by Bonner et al. (2006b, 2007). Differences between this and prior studies are the incorporation of all paths from an event and the use of an automated code to routinely process data. The automated results were subsequently reviewed; however, only automated measurements are presented. The interactive review of the measurements was used to evaluate outliers.

**Data.** The data used in this study consist of earthquakes obtained from the U.S. National Data Center (USNDC). The data were divided into two sets: 27 shallow events from the Asian continent and 143 globally-distributed events that contain a broader depth range and more path diversity (Figure 1). All events were reviewed by an analyst for validity prior to inclusion in this study.

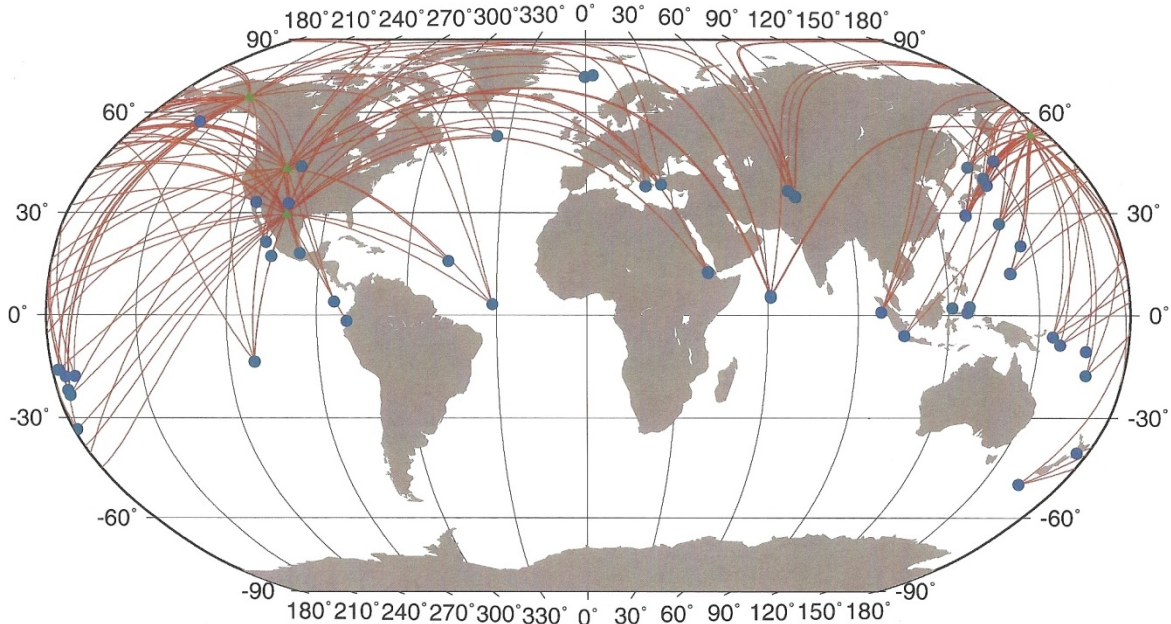


Figure 1. Representative paths showing the inclusion of oceanic, mixed, and continental components.

In order to better understand path and period-dependent effects, the data were partitioned into three period ranges: – 8–17 seconds, 17–25 seconds, and 25–40 seconds. These partitions were chosen based on the applicable period ranges of conventional  $M_s$  (17–23 seconds) and to investigate the application of  $M_s(\text{VMAX})$  to shorter (8–17 seconds) and longer periods (25–40 seconds). The 25–40-second period results are not presented in this study.

In addition, the data were also partitioned by predicted group slowness into three paths: oceanic paths ( $slow < 32.25$  sec/deg), continental paths ( $slow > 38.0$  sec/deg), and mixed oceanic-continental paths ( $32.25$  sec/deg  $< slow < 38.0$  sec/deg). This partitioning enabled determination of bias for the  $M_s(\text{VMAX})$  calculations for each path and period range. The final slowness values used in the study were empirically determined using the data and paths.

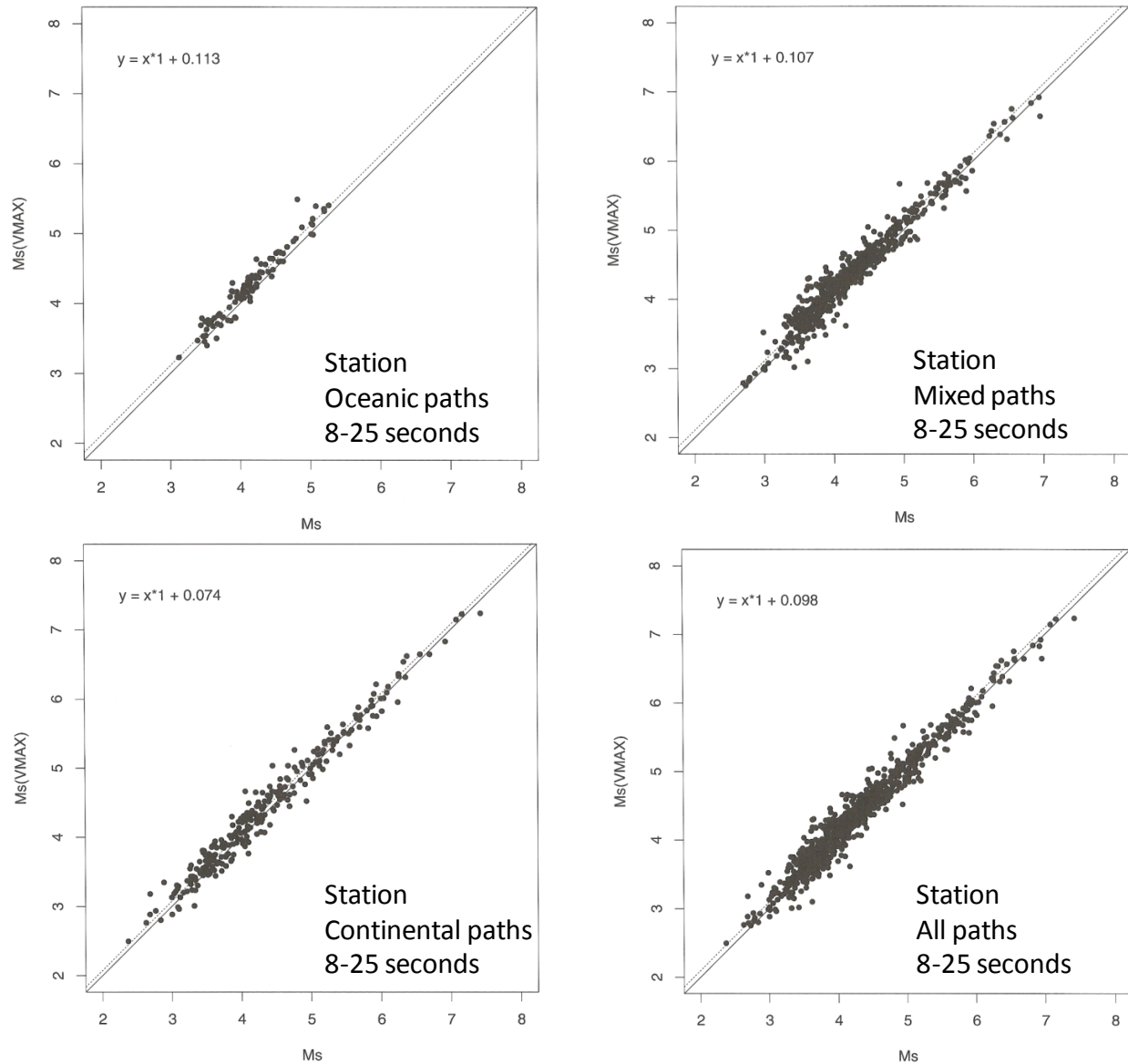
All amplitudes were corrected to displacement using frequency/amplitude/response files. Contrary to conventional  $M_s$  amplitudes measured on a long-period channel, the  $M_s(\text{VMAX})$  amplitudes were measured on a decimated broad-band channel to provide a larger period range.

**Results.** Processing of the data used an automated code to perform all calculations following the methodology outlined by Bonner (2006a, b; 2007). The waveform data were windowed using the predicted Rayleigh arrival and representative noise using predetermined parameters. The predicted group-velocity limits used a recent surface-wave group velocity model (Pasyanos, 2005).

Following the processing methodologies of Bonner et al. (2006b, 2007), once the data were windowed, the largest signal amplitude at each center frequency was selected to calculate the magnitude. Results were automatically stored using a data model within a relational database.

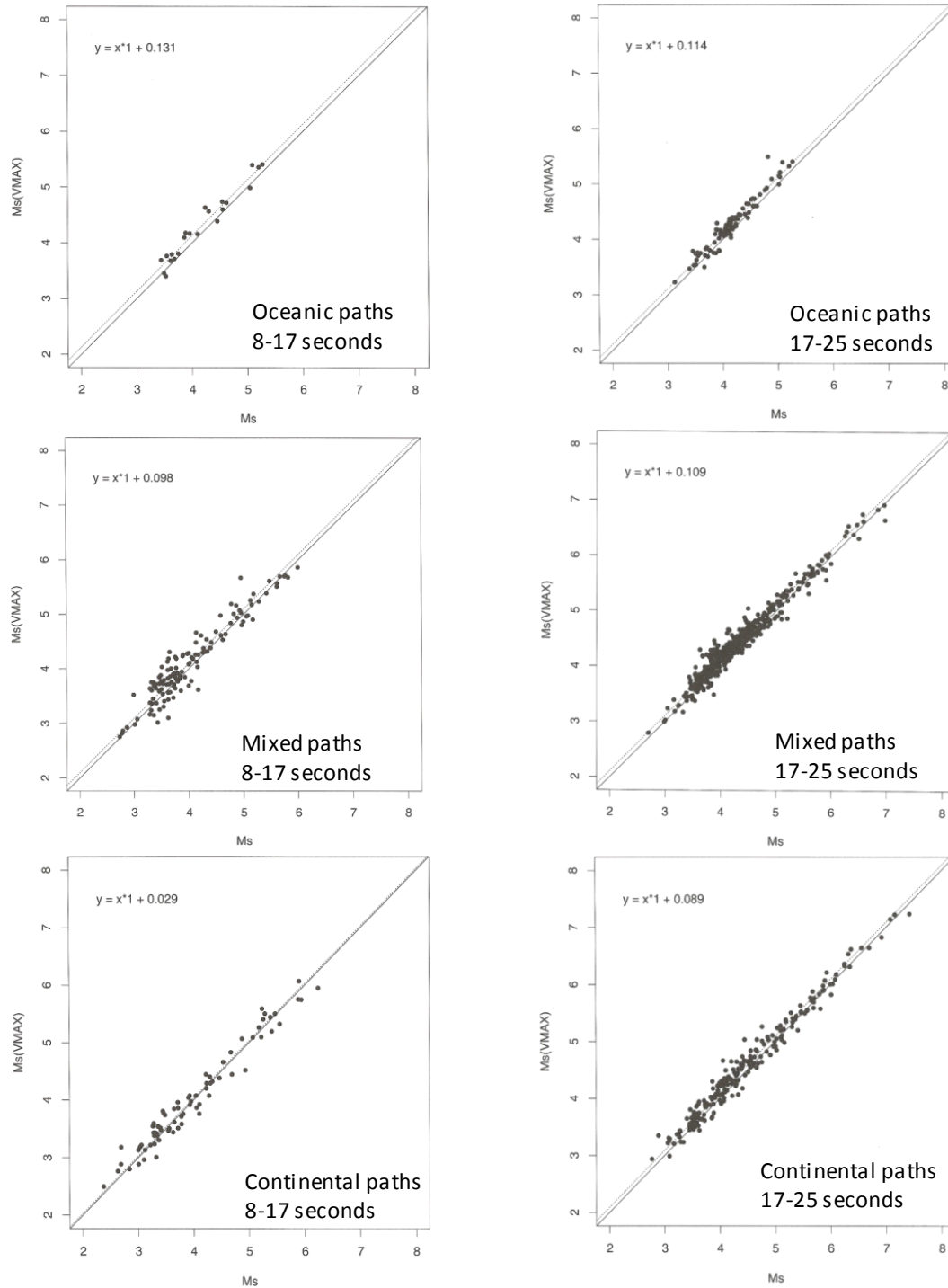
The results were compared against the standard  $M_s$  value. The Rayleigh phase amplitude for each waveform was determined by an analyst, selecting a peak-to-peak amplitude with a period in the 17 to 25 second range. An  $M_s$  formula similar to the Prague formula (Vaněk et al., 1962) was used as the comparison.

Results from the globally distributed data showing the scatter and bias at the station level are shown for the three path types, oceanic, mixed oceanic-continental, and continental, and a combination of all three types in Figure 2. Development (Russell, 2006) and early work by Bonner (2006a, b; 2007) concentrated only on continental paths. Note the nearly constant 0.1  $M_s$  unit bias. Scatter may be acceptable for an operational mode.



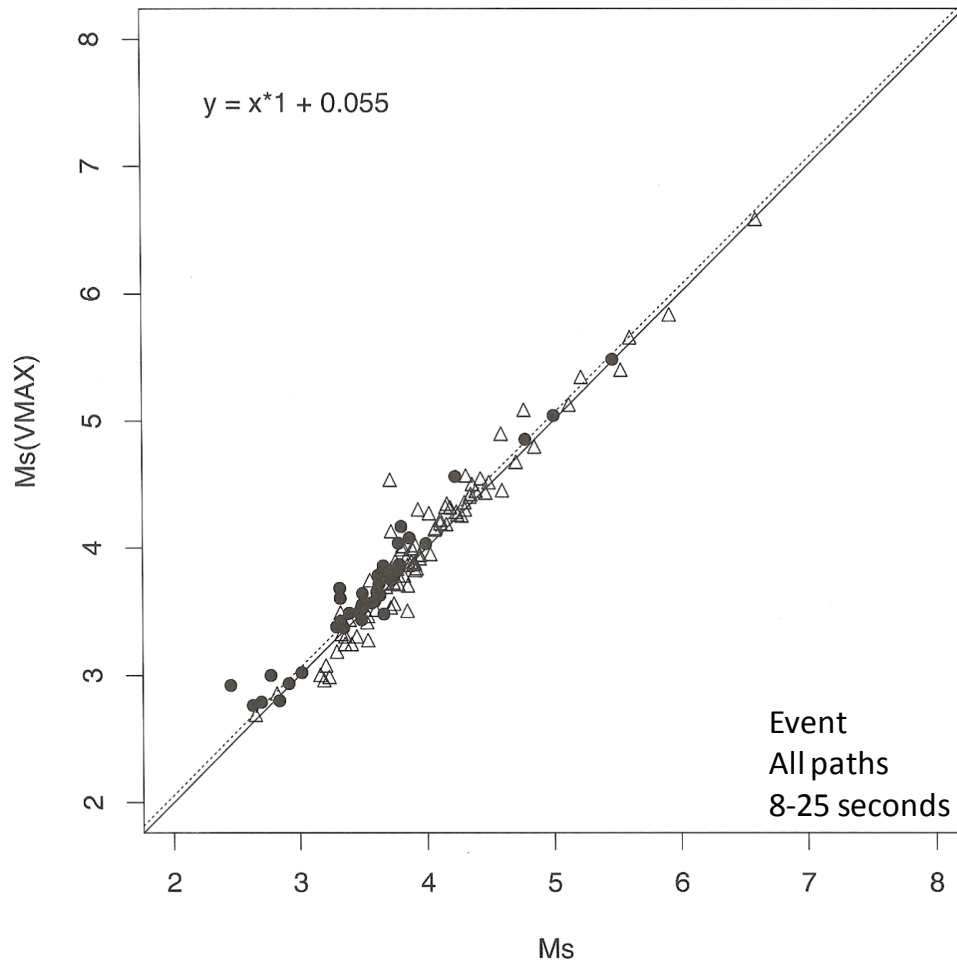
**Figure 2. Results showing the station-magnitude scatter and bias for each type of path and combined path for the investigated period range (8–25 seconds).**

We also investigated whether the bias contribution resulted from the shorter periods (8–17 seconds). To investigate this possibility, the paths were separated by period and path (Figure 3). No discernable bias is detectable. The results are consistent regardless of path and period.



**Figure 3. Results showing the station magnitude scatter and bias for each type of path and separated by period ranges to include 8–17 seconds and 17–25 seconds.**

When the station magnitudes are combined into a network magnitude for each event, similar results are observed (Figure 4). The data show good agreement with a small bias of less than 0.1  $M_s$  units. Since the Russell (2006) magnitude equation was empirically determined, any real bias terms can be incorporated into the formula.



**Figure 4. Network magnitude results with all paths for the investigated period range (8–25 seconds). The solid circles (●) represent those event magnitudes where the number of  $M_s(VMAX)$  station contributions are equal to those for  $M_s$ . The triangles (Δ) represent the event magnitudes where additional station  $M_s(VMAX)$  measurements contribute to the event average.**

In Figures 2 and 3, the scatter plots show station-magnitude data, only a direct comparison between  $M_s(VMAX)$  and  $M_s$  is possible. However, the  $M_s(VMAX)$  technique is able to determine additional station contributions not obtainable using traditional  $M_s$  techniques. Figure 4 separates those network averages to illustrate the additional  $M_s(VMAX)$  station contributions. Stated differently, those network averages marked as solid circles (●) contain equal  $M_s$  and  $M_s(VMAX)$  stations in the network magnitude. The remaining network magnitudes (Δ) have additional station contributions in the averages, all from  $M_s(VMAX)$ . The additional contributions cover the entire magnitude range. This was an unanticipated result.

Obvious outliers were examined and removed from the data. Outliers were strictly a result of processing, not methodology. For example, when two events were closely spaced, the automated group-velocity windowing may have included both events. The methodology would pick the largest amplitude, whether it corresponded to the event of interest or not. Also, automated quality-control methodologies were not implemented on the selected data. A data spike, glitch, or flat spot creates ripples in the time domain from edge effects associated with the filtering process.

Any remaining outliers could not be removed. A likely scenario is a case of two overlapping signals, two simultaneously arriving signals from different events.

## **CONCLUSIONS AND RECOMMENDATIONS**

The  $M_s$ (VMAX) technique has been known to work well for continental paths between 8–25 seconds (Bonner et. al., 2006b, 2007). However this study shows stable results for oceanic and mixed oceanic-continental paths as well. Since the data were partitioned to ensure path independence, we have demonstrated the  $M_s$ (VMAX) technique is capable of functioning as an automated replacement for  $M_s$ . This allows the inclusion of regional stations with Airy phases, and stations for which a traditional  $M_s$  may not be easily determined. Overall, the use of automated results should reduce the analyst burden of picking individual phases, only requiring checks when anomalies may be present.

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## **REFERENCES**

- Bonner, J. L., D. Russell, D. Harkrider, D. Reiter, and R. Herrmann (2006a). Development of a time-domain, variable-period surface wave magnitude measurement procedure for application at regional and teleseismic distances, Part II: Application and  $M_s$ -mb Performance, *Bull. Seism. Soc. Am.* 96: 678–696.
- Bonner, J. L., M. Pasyanos, M. Leidig, H. Hooper, and D. Harkrider, (2006b). A comparison of different surface wave magnitude measurement procedures on a Eurasian dataset, in *Proceedings of the 28<sup>th</sup> Seismic Research Review: Ground-Based Nuclear Explosion Monitoring Technologies*, LA-UR-06-5471, Vol. 1, pp. 560–569.
- Bonner, J.L., M. Pasyanos, M. Johnson, and D. Harkrider. (2007). Calibration of the  $M_s$ (VMAX) technique in Eurasia, in *Proceedings of the 29<sup>th</sup> Monitoring Research Review: Ground-Based Nuclear Explosion Monitoring Technologies*, LA-UR-07-5613, Vol. 1, pp. 541-550.
- Pasyanos, M.E. (2005). A variable-resolution surface wave dispersion study of Eurasia, North Africa, and surrounding regions, *J. Geophys. Res.* 110: B12301.
- Russell, D.R. (2006). Development of a time-domain, variable-period surface wave magnitude measurement procedure for application at regional and teleseismic distances, Part I: Theory, *Bull. Seism. Soc. Am.* 96: 665–677.
- Vaněk, J., A. Zatopek, V. Karnik, N.V. Kondorskaya, Y.V. Riznichenko, E.F. Savarensky, S.L. Solov'ev, and N.V. Shebalin (1962). Standardization of magnitude scales, *Bull. Acad. Sci. USSR, Geophys. Ser.*, no. 2, 108–111 (English Translation).